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Using qualimetric engineering and extremal analysis to optimize a proton exchange membrane fuel cell stack

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HIGHLIGHTS

- We consider the optimal configuration of a PEMFC stack.
- We utilize qualimetric engineering tools (Taguchi screening, regression analysis).
- We achieve analytical solution on a restructured power-law fitting.
- We discuss the Pt-cost involvement in the unit and area minimization scope.

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ABSTRACT

The optimal configuration of the proton exchange membrane fuel-cell (PEMFC) stack has received attention recently because of its potential use as an isolated energy distributor for household needs. In this work, the original complex problem for generating an optimal PEMFC stack based on the number of cell units connected in series and parallel arrangements as well as on the cell area is revisited. A qualimetric engineering strategy is formulated which is based on quick profiling the PEMFC stack voltage response. Stochastic screening is initiated by employing an $L_9(3^3)$ Taguchi-type OA for partitioning numerically the deterministic expression of the output PEMFC stack voltage such that to facilitate the sizing of the magnitude of the individual effects. The power and current household specifications for the stack system are maintained at the typical settings of 200 W at 12 V, respectively. The minimization of the stack total-area requirement becomes explicit in this work. The relationship of cell voltage against cell area is cast into a power-law model by regression fitting that achieves a coefficient of determination value of 99.99%. Thus, the theoretical formulation simplifies into a non-linear extremal problem with a constrained solution due to a singularity which is solved analytically. The optimal solution requires 22 cell units connected in series where each unit is designed with an area value of 151.4 cm^2. It is also demonstrated how to visualize the optimal solution using the graphical method of operating lines. The total area of 3270.24 cm^2 becomes a new benchmark for the optimal design of the studied PEMFC stack configuration. It is discussed the viability of our solution with respect to the performance of the main stack cost driver, i.e. the platinum loading costs. In conclusion, the proposed technique is simple and practical offering more accuracy, convenience and flexibility when compared with other competing algorithmic schemes.

1. Introduction

Fuel cells epitomize a future source for clean energy [1]. This is because fuel cells do not overburden the environment with reaction side-products. At the meantime, fuel cells take advantage of recyclable reaction processes that replenish the energy generation cycle without the need to consume or transform permanently large quantities of natural resources [2]. An efficient representative of the fuel cell technology is the proton exchange membrane fuel-cell (PEMFC) [3]. PEMFCs exhibit great range of application in portable and back-up power demands as well as in distributed generation [4–7]. The high efficiency realized for transportation purposes makes PEMFCs strong competitors against other popular renewable resources that seek to extract energy from solar or wind engineering applications [8–10]. Recently, it has been recognized that a great volume of research has been conducted with respect to mak-

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ing the PEMFC technology more efficient and marketable [11]. However, studies on how to optimally design a PEMFC stack configuration are still under development. It is striking that in the latest review by Secanell et al. [12], the authors found that only two examples of stack optimization attempts have been brought to light, thus, essentially motivating the research community to converge on this subject. Stack optimization should be a perplexing theme because of the vast diversity of technologies involved today. At the same time, this offers many opportunities for studying systematically the optimal stack configuration problem since there are various versions of PEMFC units to be considered. In turn, this poses a major challenge in succeeding to model generically and in a coherent fashion an optimal PEMFC stack arrangement. As a matter of fact, in the state-of-the-art review by Khan et al. [13] it was concluded that there is not a particular uniform manner in order to classify PEMFC computational modeling. The same group reported that various subclasses have been formed reflecting the individual viewpoint of a few experts depending solely on their strict fields of specialization. Thus, the subclasses that have been propounded as of now are differentiated to emphasis areas which are related to: (1) thermal, flow and/or electrochemical analysis, (2) analytic, semi-empirical or mechanistic modeling, (3) geometric dimensioning, and (4) length scaling [13]. Therefore, it becomes apparent that there is great opportunity to attack the PEMFC stack optimization problem by focusing each time to different aspects of it. Since the review by Secanell et al. [12], there have been published six additional articles regarding the issue of PEMFC stack optimization, thus essentially declaring the emergence of a new field [14–19]. Ostensibly, optimizing concurrently the PEMFC unit cell performance and the stack design is a formidable task resisting analytical ingenuity due to the great depth of multidisciplinary knowledge that is required to be incorporated in an impending model. Assuming that a complete model has been contrived that espouses both of those design issues, the derived model complexity would still be anticipated to be computationally insurmountable. Therefore, the trend that surfaces from the current endeavors in the scientific community is to split the optimization problem by selecting to fix the parameters in either the stack design or the unit cell or even partly intermingling some parameters from both systems. Specifically, working with the design of a PEMFC stack, the primary responses that were sought to be optimized were the stack output voltage and the stack demand current, or equivalently the daily power demand for the intended application. In turn, researchers attempted to resolve the PEMFC stack performance by maintaining constant either the cell parameters, i.e. cell absolute temperature, membrane resistivity, thickness of the PEMFC and the partial pressures for hydrogen and oxygen, correspondingly [14,16–19], or the PEMFC stack design characteristics, i.e. the number of PEMFC units in series and parallel connection along with the single cell size expressed by the its effective area [15,20]. It is worthwhile to note that all published work on the PEMFC stack optimization problem has involved highly sophisticated computational tactics for reaching to a viable solution, thus testifying to the onerous nature of the problem. Tackling the numerical solution for each of the cited computational models demanded the implementation of the best known machine-based solvers such as: genetic algorithms [17,26], differential evolution [14], heuristics [15], bio-inspired P systems optimization [16], particle swarm optimization [18–19] and simulated annealing optimization [20]. Generally speaking, the optimization of dynamic response of hybrid systems that consist of PEMFC in parallel with a battery pack will also be benefited from effective solver approaches [21]. Perturbation algorithms have been developed to treat even more troublesome circumstances such as the impossibility of measuring directly the oxygen excess ratio in a PEMFC system [22]. Capturing process details will be important for high-efficiency stand-alone systems where a design calls for an integration of a PEMFC unit with an auto-thermal ethanol reformer [23]. Non-linear modeling may be extended to include extraneous mechanistic uncertainties such as in adjusting air-feed in a PEMFC where robust control is imperative [24]. Of course, the optimization of microgrid operations against time-varying requests utilizing Model Predictive Control will enhance the information collection process for economic efficiency in modern designing of PEMFCs [25].

In this work, emphasis is placed on formulating an easy-to-apply solver which offers better accuracy in solving benchmarked optimal PEMFC stacks. The unit cell parameters are maintained constant in order to track down the optimal solution for the stack configuration. The simple zero dimensional, isothermal mechanistic model as originally proposed by Mohamed and Jenkins [26] is treated in search of the minimum number of PEMFC units connected in series and parallel arrangements along with the optimal cell unit area subject to a specification for a nominal voltage and output power. Historically, it was in 2004 that for the first time the PEMFC optimization problem was defined in a well organized fashion by Mohamed and Jenkins [26]. In their comprehensive study, the authors demonstrated that starting with basic information from key parameters for a typical PEMFC unit they proceeded to configure a stack design that delivered maximum power at nominal voltage. To succeed in that endeavor, the authors sought and obtained the necessary input for their PEMFC stack optimization study by performing a preliminary experiment on a single prototype cell unit which then was used for fitting the stack configuration variables. The optimized quantities were the stack output (terminal) voltage and power constrained to perform with a minimum number of cell units and optimal cell size in a network of units connected in series and parallel configuration. The solution has been understood to be intractable analytically in spite of being a well-formulated problem of pure deterministic nature [15,26]. Moreover, the authors recognized that the final solution had to comply with a couple of practical limitations that needed to be revisited if the solution was to become viable. One had to do with keeping the count of PEMFC units in the optimal stack as low as possible due to their appreciable unit cost as well as to their direct impact on impeding storage restrictions. The other constraint had to do with the size of the cell unit itself which also entailed cost and storage ramifications. Thus, the cell size was also necessitated to be suppressed in the optimal solution. Therefore, it became clear for the first time that the number and the size of cell units ought to be minimized concurrently thus achieving a global solution. Subsequently, the authors [26] were successful in reaching an optimal solution utilizing a genetic algorithm to circumvent the analytical intractability of their well-posed theoretical model. The solution provided by Mohamed and Jenkins [26] has essentially been confirmed recently [15]. Chakraborty [15] realized the enormous importance of the work by Mohamed and Jenkins [26] and he reconsidered the problem by developing a new empirical algorithm based on a sophisticated stochastic-heuristic approach. In turn, Chakraborty [15] demonstrated that his optimal solution is solid as he compared his method with three other well-accepted approaches which were based on: (1) a genetic algorithm, (2) a simulated annealing method and (3) the (1 + 1) EA technique. At this point, it may be argued that the problem originated by Mohamed and Jenkins [26] has factually been benchmarked toward reaching a global solution. In summary, the PEMFC stack configuration problem does not yield to an analytical manipulation. In lack of an exact solution, it was further anticipated that resorting to a numerical solution with probably ordinary iterative methods was to be computationally challenging if not prohibitive.

Acceding to Chakraborty's insight [15], there is a sustained demand for delivering reliable stack design predictions on a regular basis in the future. Since new models of PEMFC units will be